

THE RADIATION OF HEAT FROM THE HUMAN BODY. IV. THE EMISSION, REFLECTION, AND TRANSMISSION OF INFRA-RED RADIATION BY THE HUMAN SKIN

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INTRODUCTION

Although the absorption and reflection by skin of ultra-violet and visible radiation has been studied extensively, beginning with the spectrographic observations of Hasselbalch (1) in 1911, there has been relatively little investigation of these properties of the skin in respect to the infra-red region of the spectrum. This is especially true of the spectroscopic study of the skin in relation to infra-red radiation, as most of the investigations reported in the literature have been carried out by means of filters.

Our interest in the long wave length reflecting and transmitting powers of the skin lies in the relation of this form of radiation to the heat regulating mechanism of the body. As is well known, the heat produced by the human body is dissipated to the environment by evaporation, conduction, convection, and by radiation. Much evidence has accumulated in the course of studies of skin temperature (Aldrich (2), Cobet and Bramigk (3), Hardy (4)), not only that the radiation loss occurs entirely within the infra-red region of the spectrum, as would be expected, but that within the range of effective radiation the skin obeys the laws of black-body emission. As a consequence, one would expect to find no reflection and, conversely, complete absorption of radiant energy within this range of the spectrum by the outermost layers of the skin, since the radiating character of a body depends on the nature of its surface.

Sonne (5) carried out some experiments on reflection by skin-like surfaces of radiation in the visible and in the so-called "inner" and "outer" infra-red regions of the spectrum, using filters, and found 35 per cent reflection in the visible and "inner" infra-red and no reflection in the "outer" infra-red. By means of needle thermocouples he also observed the transmission through living skin and reports a gradient of temperature from without inward with a maximum 0.5 cm. below the skin surface in the case of visible and "inner" infra-red, while the "outer" infra-red showed little power of penetration, the maximum heating effect occurring at the surface. Loewy and Dorno (6) report similar penetration by the visible and shorter waved infra-red and similar impenetrability of the

longer waved infra-red. Bachem and Reed (7), in the course of experiments on transmission through various layers of skin of light, chiefly in the ultra-violet and visible but extended to include the infra-red out to $1.4\ \mu$, found increasing absorption in the outer layers with increasing wave length. Danforth (8) and Cartwright (9) have studied spectroscopically the transmission of visible and infra-red through the human cheek and their curve shows penetration only between $0.54\ \mu$ and $1.5\ \mu$ with a peak at $1.15\ \mu$.

As may readily be appreciated the above mentioned experiments by previous workers lend support to the theory that the skin, although it reflects and transmits considerable visible energy and energy in the infra-red, is virtually a perfect absorber in the region beyond $3\ \mu$, which Plank's equation gives as the range of the spectrum in which a body at the temperature of human skin radiates energy. The evidence, however, is fragmentary and there do not exist, to our knowledge, any comprehensive spectroscopic studies of the absorptive and emissive properties of the skin throughout the region of the infra-red spectrum in which the body radiates energy. In addition to the experiments already mentioned, however, which have bearing on the probable black-body character of the skin, are the experiments on transmission of Pauli and Ivancevic (10), Gaertner (11), and Pearson and Norris (12) and the measurements of the emission spectrum of skin recently reported by Wright and Telkes (13).

The following experiments fall into three groups: (1) Experiments on the emission spectrum of the skin compared to the emission spectrum of an experimental black-body. (2) Experiments on the infra-red reflection spectrum of skin. (3) Experiments on the infra-red transmission (absorption) spectrum of skin. In the first two groups living human skin has been used as the subject of the experiments. In the third group, skin from freshly amputated surgical specimens and epidermal layers of skin, obtained by blistering with cantharides plasters, were used.

METHOD

A reflecting infra-red prism spectrometer equipped with a rock salt prism of refracting angle 60° , Wadsworth mounting, and adjustable slits was used in conjunction with a vacuum thermocouple connected to a Leeds and Northrup high sensitivity galvanometer. A schematic drawing of the apparatus is shown in Figure 1 in which S_1 and S_2 represent the slits of the spectrometer, P the prism, M_1 , M_2 , M_3 , plane mirrors, C_1 , C_2 , C_3 , concave spherical mirrors, O the axis of rotation of prism table, and T the thermocouple. Amplification of the galvanometer deflections was secured by a thermo-element device and a second galvanometer but the sensitivity of the apparatus without amplification was actually sufficient and the amplifier was used only in some of the experiments upon skin emission. A

Nernst glower was used as the energy source for the experiments dealing with reflection and transmission. Calibration of the spectrometer was carried out by the determination of eight points, viz., quartz reflection peak at $12.5\ \mu$, quartz reflection peak at $8.9\ \mu$, CO_2 emission peak at $4.35\ \mu$, water absorption band at $2\ \mu$, mercury arc infra-red line at $1\ \mu$, visible red at $0.75\ \mu$, visible yellow at $0.58\ \mu$, and visible green at $0.54\ \mu$, and a calibration curve was plotted through these points. The mounting of the skin specimens, in relation to the energy source and the entrance slit of the spectrometer, will be described in the sections devoted to these experiments. The slits used in the experiments were for the most part fairly wide, $0.3\text{--}0.4\ \text{mm.}$, but in some regions of the spectrum when working with very thin layers of skin in the transmission experiments, very narrow slits, $0.05\ \text{mm.}$, were used. For the emission experiments, because of the low intensity, very wide slits, $1\ \text{mm.}$ had to be used. The data given below are without slit width corrections.

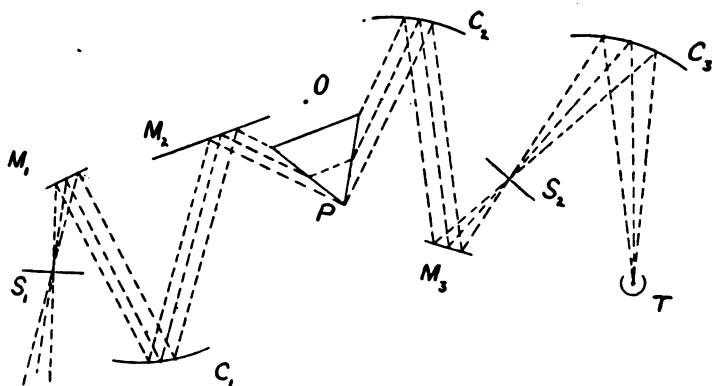


FIG. 1. SCHEMATIC DIAGRAM OF SPECTROMETER

EXPERIMENTAL

1. EMISSION SPECTRUM OF HUMAN SKIN

The subject's finger was held immediately in front of the spectrometer slit, and readings of the galvanometer deflections were made at $5'$ intervals on the spectrometer scale. Between each reading the finger was removed and the galvanometer allowed to return to the zero point. Similar observations were then made on a Leslie cube, the cone of the cube being applied to the window in the spectrometer housing just before the slit. The Leslie cube was used as an experimental black-body and was maintained at a temperature as close to that of the subject's skin as possible throughout the period of observation. The measurements of skin temperature were

made with the radiometer previously described. The results of one such experiment are given in the form of a curve (Fig. 2), in which wave lengths are plotted as abscissae and galvanometer deflections as ordinates. Amplification of the galvanometer deflections was employed. Other similar experiments, with and without amplification, gave similar results and are not reproduced here. Examination of the figures reveals that the skin emission curve and the Leslie cube emission curve are nearly superimposable. The latter has been shown by Hardy (4) to agree within 1 per cent with the theoretical curve for black-body emission derived from Planck's formula. The absorption bands present in the curve are of no significance as they are due to the protective lacquer coatings on the collimating mirrors of the spectrometer. The presence of the band at 8μ , however, accounts for the apparent shifting of the maximum from its theoretical position at 9μ to its observed position at 6μ . The location of the cut-off in the near infra-red, as may be seen, lies somewhere between 2μ and 3.5μ , its exact location probably nearer 3.5μ since the slit widths were necessarily large and the data are plotted as observed, that is, without slit width corrections. Essentially the same results were obtained by Wright and Telkes (13).

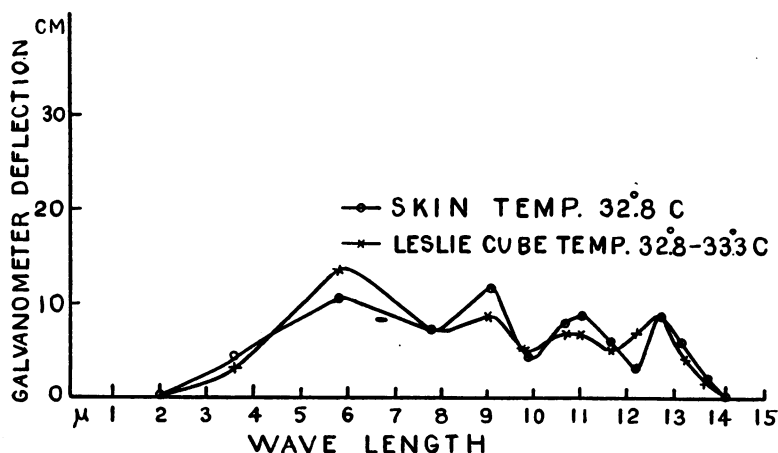


FIG. 2. EMISSION CURVE OF HUMAN SKIN AND OF LESLIE CUBE

2. INFRA-RED REFLECTION SPECTRUM OF HUMAN SKIN

The study of reflection obviously offers difficulties because of the diffuse character of reflection from the skin. The method chosen was to compare the reflection from skin with that from a substance of known reflecting power. To do this it is, of course, necessary to use a substance which reflects diffusely and the total reflection of which over the entire hemisphere is known. If the surface chosen obeys Lambert's law of dif-

fuse reflection to the same extent as the skin it is only necessary to make the comparison at a single angle of reflection. The total reflection of the skin will then be given by the expression $(I_\theta/I'_\theta) \times R' = R$ where I_θ is the energy reflected at angle θ from skin, I'_θ the energy reflected at angle θ from the comparison substance, R' the total reflection from the comparison substance and R the total reflection from the skin. The substance used for comparison in the following experiments was a scraped block of magnesium carbonate. The total reflecting power of this substance has been determined by Coblentz (14) at five wave lengths between 0.6μ and 24.0μ .

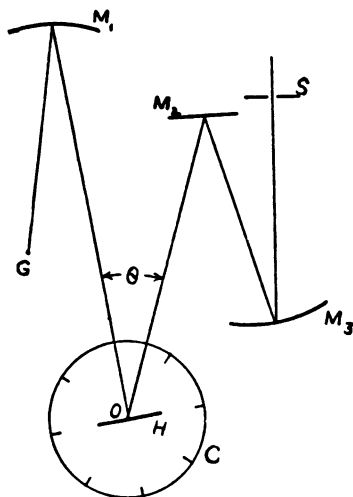


FIG. 3. DIAGRAM OF EXTERNAL OPTICAL SYSTEM FOR REFLECTION AND TRANSMISSION EXPERIMENTS

To test Lambert's law an apparatus was devised, after the manner of Hutchins (15), to serve as an external optical system. A schematic diagram of the system is shown in Figure 3, in which S represents the entrance slit of the spectrometer, G the Nernst glower, H a brass holder with rectangular aperture against which the specimen for examination is applied, M_1 and M_3 concave mirrors, and M_2 a plane mirror. The holder H is mounted so that it may rotate with respect to a graduated circle C but so that it is fixed with respect to M_1 and G and that the incident beam is normal to the reflecting surface. G , M , and H thus rotate together about the point O . With this arrangement, when the image of G is focussed at O , if M_2 and M_3 are properly adjusted, the light diffusely reflected from O at any angle θ always falls upon the slit S . Measurements were made of the energy reflected at various angles from the normal from each of the substances while the spectrometer was set at 1.3μ and also with the spectrometer set at 3.6μ . The results are shown in Table I where θ denotes

the angle of reflection, I_θ the galvanometer deflection (intensity of reflected beam) for skin at angle θ , I_θ' the galvanometer deflection for magnesium carbonate at angle θ . The ratios $I_\theta/\cos \theta$ and $I_\theta'/\cos \theta$ should in each case be constant according to Lambert's law. The results show that

TABLE I

Tests of Lambert's Law of diffuse reflection for skin and magnesium carbonate surfaces

Wave length	θ	$\cos \theta$	Skin		Magnesium carbonate	
			I_θ	$I_\theta/\cos \theta$	I_θ'	$I_\theta'/\cos \theta$
μ	degrees		cm.		cm.	
1.3	20	.940	2.2	2.34	11.5	12.2
	30	.866	1.9	2.19	10.3	11.9
	40	.766	1.9	2.49	9.8	12.8
	50	.643	1.5	2.33	7.8	12.1
	60	.500	1.5	3.00	6.6	13.2
3.6	20	.940	3.0	3.19	8.2	8.73
	30	.866	2.6	3.00	7.8	9.00
	40	.766	2.3	3.00	7.6	9.90
	50	.643	1.8	2.80	5.5	8.55
	60	.500	1.5	3.00	4.2	8.40

in fact the ratio is very nearly constant for each of the substances. In general, the findings indicate that the skin and the magnesium carbonate surface both follow Lambert's law sufficiently closely to enable one to use the latter as a standard for determining the reflectivity of skin.

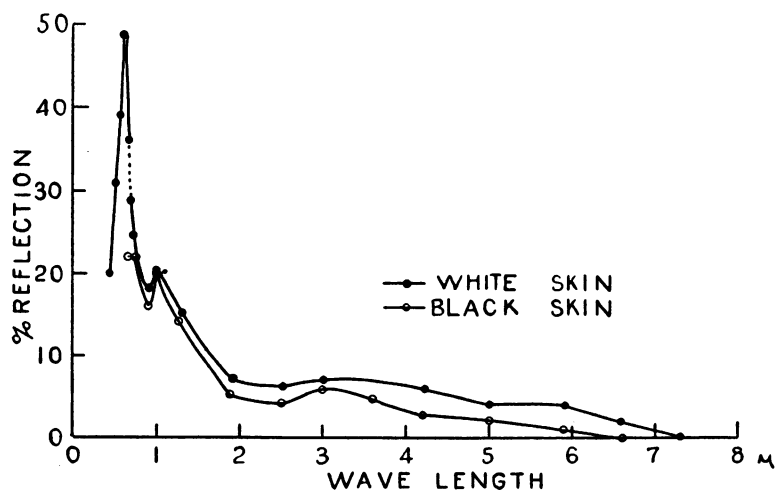


FIG. 4. REFLECTION OF WHITE AND OF NEGRO SKIN

Figure 4 shows the percentage reflection from white and negro skin in the infra-red, as measured in the manner outlined above, using the same optical arrangement as that used in the tests of Lambert's law. The angle θ was maintained at 20° and direct comparisons between the skin and the block of magnesium carbonate were made at each spectrometer setting. The skin of the volar surface of the forearm was used. On white skin measurements were also made in the visible, using a Koenig-Martens spectrophotometer instead of the infra-red spectrometer. The dotted line indicates the discrepancy, 7 per cent, between the spectrometer measurements and the spectrophotometer measurement at 0.7μ . The discrepancy is undoubtedly due to inaccuracy of the spectrometer method in this region of short wave lengths, since the energy of the Nernst glower source is low here and the galvanometer deflections are correspondingly small with large percentage error. It is for this reason that the spectrophotometer was used throughout the visible range.

The significant findings on examination of the curves are that there is a sharp falling off in reflecting power at about 2μ , in the region of the cut-off in the near infra-red of the skin emission curve, and that beyond this region the reflection is only in the neighborhood of 5 per cent. It is also significant that the amount of reflection in the infra-red is about the same for negro skin as it is for white skin.

3. TRANSMISSION SPECTRUM OF HUMAN SKIN

In the study of transmission it was obviously necessary to use dead skin unless animals were to be employed. Accordingly, fragments of human skin were obtained from specimens from surgical amputations and kept moist with normal saline solution up to and during the time of making the observations. This was always on the day on which the specimen had been removed from the patient. The pieces of skin thus obtained by trimming with a scissors or stripping with a knife from the underlying subcutaneous adipose tissue of the amputated breast or leg were quite thick and required further shaving down to eliminate as much of the adherent subcutaneous tissue as possible. This was attempted by means of a freezing microtome but, with the size of the skin specimens required, it was found impossible; therefore, instead of shaving with a microtome knife, after freezing on the stage of the microtome, the specimens were filed down to the desired thickness with a hand file. In all specimens so treated, it was found later by cross sectioning and appropriate staining, that all the layers of skin were left intact and that a thin layer of subcutaneous tissue also remained. For studying the transmission of the epidermal layers of skin alone, specimens were obtained by means of blistering the skin of living subjects with cantharides plasters and, about twelve hours after application of the plaster, removing the layers of epidermis separated by this process. These speci-

mens were then similarly kept moist with saline solution and examined on the days of their removal from the subjects. They were also constantly kept moist with the saline solution by sponging during the period of spectroscopic examination. The small amount of water on the tissue during the time of measurement could not have represented a film of greater thickness than 0.05 mm. Such a thickness transmits the infra-red readily.

The external optical arrangement for most of the transmission experiments was similar to that used in the reflection experiments, the only differences being that the angle θ , Figure 3, was set at 180° , for the direct transmission, and that a new holder was substituted which was so constructed that the skin could be stretched over a rectangular hole, 2×1 cm., in the holder. The holder was set, similarly to the one used in the reflection experiments, so that the plane of the surface of the skin was normal to the incident beam. By this arrangement the effect of scattering could be studied as well as the direct transmission, since by changing θ from 180° the energy of the radiation emerging at various angles from the direct path could be measured. The transmission curves shown in the accompanying figures, however, are not corrected for scattering but represent the ratio of the deflection caused by the directly transmitted beam to the deflection caused by the incident beam, expressed in percentage. The observation on the energy of the incident beam at each point in the spectrum was not made immediately after each observation on the skin since it was necessary to dismount the skin from the holder. The entire spectrum was therefore explored first with the skin in place and then with the empty holder, or vice-versa. The transmission values are calculated from the ratio of the galvanometer deflections produced by the energy transmitted directly through the skin to the deflections produced by the energy of the direct beam with the skin removed.

A. Transmission through entire thickness of skin

Only one of the experiments on transmission through the entire thickness of the skin is reproduced here (Fig. 5) since all show similar results, that is, practically complete absorption. In some of the experiments instead of using the external optical system described above, the number of mirrors was reduced to one and the skin specimen was held about two centimeters before the spectrometer slit, to determine whether there was a significant loss due to the number of mirrors; but the results were essentially the same. The curve shown is for a piece of skin which, measured after fixation and staining, was found to be 1 mm. thick, about half of its thickness being actual skin and the rest adherent subcutaneous tissue. The slit widths necessary for producing any significant deflection when this very opaque, thick skin was interposed were so large (1 mm.) that the comparative measurements on the incident beam gave too large deflections to be

read directly and the transmission ratios had to be interpolated, through the major portion of the spectral region concerned, by further comparison with reduced slit widths. Therefore, the recorded transmission values cannot be considered more accurate than ± 2 per cent in absolute value, but can be considered as giving the order of magnitude of the percentage transmission.

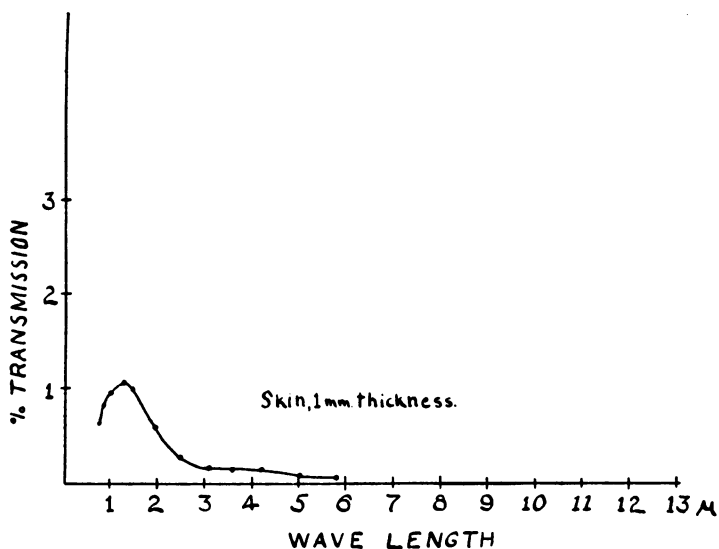


FIG. 5. TRANSMISSION THROUGH SKIN AND SUBCUTANEOUS TISSUE, THICKNESS 1 MM.

These results, of extremely low penetrability even in the near infra-red, do not agree with the findings of most previous workers. Danforth (8) and Cartwright (9) obtained appreciable amounts of transmission out to about 1.5μ through thicknesses of skin and subcutaneous tissue greater than those studied by us. It is possible that the fact that we were using skin that was dead and had been frozen while their work was carried out on the living tissues accounts for the discrepancy, although the work of Bachem and Reed (16) has shown that in the ultra-violet and visible there is little difference between the penetration through living and through dead tissue. The results of Pauli and Ivancevic (10) and of Gaertner (11) are also in apparent disagreement with ours but their methods, which involve placing the specimen close to the receiving thermo-element, sometimes in front of and sometimes behind the exit slit, are open to the objection that re-radiation is not eliminated. Unfortunately, we could not study the effect of scattering by the thick pieces of skin but our observations on scattering by the thinner epidermal pieces, to be recounted below, are in total disagreement with the observations on scattering of Pauli and Ivancevic.

They found large amounts of energy at all angles of emergence, contrary to our own findings, but did not distinguish between actually transmitted scattered radiation and re-radiation due to heating of the skin, a distinction which can only be made if the specimen is placed in front of the dispersing prism. In agreement with our results are those of Aldrich (2) who measured the total transmission through skin 2 mm. thick and found it to be negligible in amount.

B. Transmission through epidermis

The transmission curves of several pieces of epidermis obtained by blister from the volar surface of the forearm of each of three individuals are shown graphically in Figure 6. The specimens were sectioned and

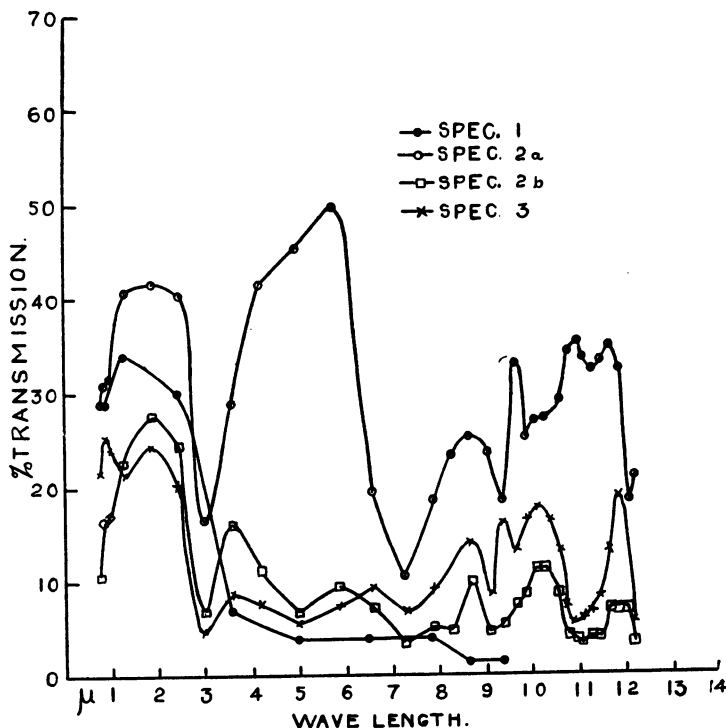


FIG. 6. TRANSMISSION THROUGH EPIDERMIS

Specimen 1. White corneum and Malpighium, thickness 0.12 mm. Specimen 2a. White corneum, thickness 0.03 mm. Specimen 2b. White Malpighium, thickness 0.08 mm. Specimen 3. Negro corneum, thickness 0.14 mm.

stained with hematoxylin and eosin, after the experiments, to establish which layers of epidermis were included in each piece of skin studied. Specimen 1 is skin from a white man and includes the corneum and a large part, if not all, of the Malpighian layer, thickness 0.12 mm. Specimen 2

is also white skin but in this case separation between the corneal layer (2a), thickness 0.03 mm., and the Malpighian layer (2b), thickness 0.08 mm., was fortuitously obtained, the corneum having at first adhered to the cantharides plaster and the Malpighian layer to the raw surface of the arm. Specimen 3 is from the arm of a very dark negress and consists of the corneal layer from which most of the Malpighian layer was apparently lost in removal. Its thickness, 0.14 mm., is considerably greater than that of the corneum of white skin, in fact it is approximately that of the corneal and Malpighian layers of white skin taken together. Its opacity also is greater than that of the white corneum, but is slightly less, in the longer wave lengths at least, than that of the white Malpighian layer. It is a question whether the intermediate position of this curve is due entirely to the thickness of the negro corneum or whether it is also partly due to the presence of a few scattered cells of the underlying Malpighian layer. Pigment is, of course, also present, but the amount is not large in the outer layers which are under consideration.

On studying the curves it is seen that in the near infra-red there is considerable transmission through both corneum and Malpighian layer but that beyond 3μ , while the corneum still transmits a large percentage of energy, the transmission through the Malpighian layer alone and through thicknesses containing both layers falls off markedly. It will also be observed that in Curves 2a, 2b, and 3 there are well marked absorption bands and that the most prominent of these is present in all three of the curves. This band is not found in Curve 1 because the points were taken too far apart to resolve it.

The results of the experiments on transmission through epidermis agree in general with the findings of Pearson and Norris (12) who made similar studies, but only to 5μ . The greater percentage transmission found by them may be accounted for partly by the fact that the layer of skin used was thinner than any studied by us, but is probably also due to the fact that, in the effort to correct for scattering, they placed the specimen behind the exit slit and in close proximity to the thermopile, thus introducing the error of re-radiation.

The effect of scattering

The effect of scattering was studied in the transmission experiments on the thin layers (epidermis). The skin holder was mounted, as previously mentioned, on the same graduated circle used for the reflection experiments. In studying the direct transmission the holder *H* (Fig. 3) was maintained in such position that θ was 180° . The energy of scattered beams emerging at various angles from the direct beam could now be directly measured by rotating to any desired angles away from 180° . The results of such experiments, made at several different points in the

TABLE II

Intensity of transmitted radiation scattered at various angles. Epidermis

Wave length	θ	Angular deviation of transmitted beam from the normal ($\theta = 180^\circ$)	Galvanometer deflection
μ	<i>degrees</i>	<i>degrees</i>	<i>cm.</i>
0.7	200	+20	0.2
	180	0	8.3
1.9	220	+40	0.1
	210	+30	0.2
	200	+20	0.8
	180	0	37.7
	160	-20	1.3
	150	-30	0.3
2.5	210	+30	0.2
	200	+20	0.8
	180	0	48.5
6.6	200	+20	0.0
	180	0	4.8
11	200	+20	0.1
	180	0	4.5

spectrum, are shown in Table II, in which the angles are given in degrees of rotation in either direction (plus and minus) from the position $\theta = 180^\circ$. It is apparent from the data that the loss of energy by scattering is not great even at angles as small as 20° and is practically negligible at 30° . It is also seen that the scattering decreases with increase in wave length, as would be expected. Although the results of experiments such as these do not lend themselves to accurate calculation of the energy loss by scattering and cannot be applied in the form of correction factors to the transmission curves, they show qualitatively that the form of the transmission curves would not be materially altered if the loss from scattering could be eliminated and also that the loss, absolutely considered, is small.

It is to be emphasized again that the magnitude of scattering cannot be determined and scattering cannot be corrected for by methods which involve placing the specimen in close proximity to the receiving thermoelement, either before or behind the exit slit of the spectrometer, because it is then impossible to distinguish between actual scattering and re-radiation. The importance of eliminating the latter has been pointed out by Aldrich (2) in his work on total transmission of heat radiation through skin.

The structure of the transmission curves

As previously mentioned, the transmission curves of epidermis show well marked absorption bands of which the ones in the neighborhoods of

3, 7, 9, 11, and 12.5 μ are present in all of the three curves in which observations were taken sufficiently close together in the spectrum to resolve the bands. The most prominent of these bands is the one at 3 μ which is probably a combination of the characteristic water band at 2.95 μ , NH_2 band at 2.96 μ , and CH_3 band at 3.43 μ . This band was previously observed by Pearson and Norris (12), who also predicted the presence of the 6 μ band. Very similar structure has been found by Dr. W. W. Coblenz of the U. S. Bureau of Standards in unpublished experiments on the infra-red transmission spectrum of the bat's wing. Lucas (17) has shown that the ultra-violet absorption spectrum of the skin closely resembles that of a number of protein compounds and amino acids. Investigation of similar relationships in the infra-red are now under way. There are not now available transmission curves of such substances with which

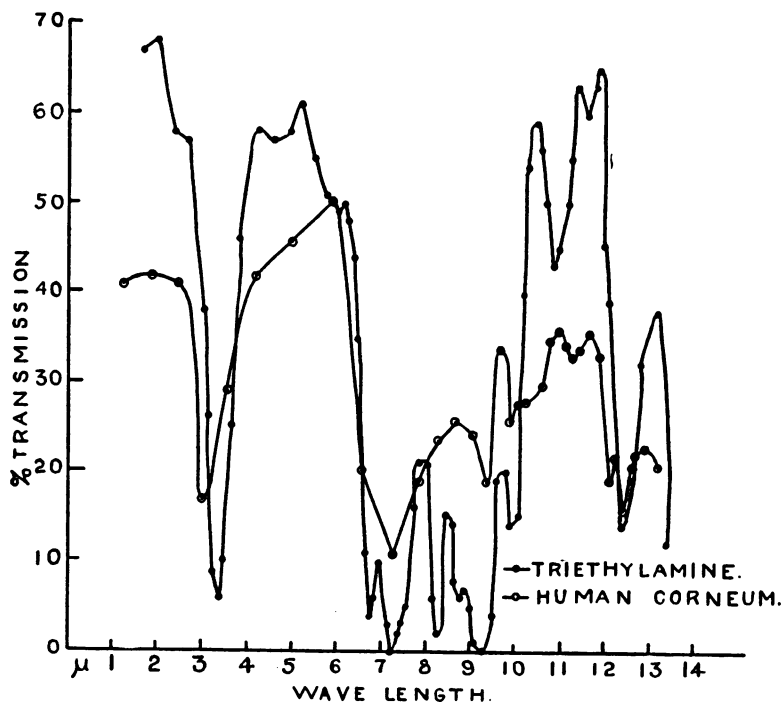


FIG. 7. TRANSMISSION OF HUMAN CORNEUM AND OF TRIETHYLAMINE

to compare the transmission curves of skin. Figure 7 shows the transmission (absorption) spectrum of human corneum compared with that of triethylamine, as given by Coblenz (18). The general similarity of the curves is of course of no significance except in so far as it emphasizes the probability that the structure of the skin curve is largely determined by the carbon and nitrogen containing radicals in the organic substances composing the skin.

CONCLUSIONS

The energy distribution curve of the radiation of the normal human skin has been found to correspond with that which would be expected of a physical black-body of the same temperature. The low reflecting and transmitting power of the skin for radiation in the region of the spectrum in which the skin radiates is further evidence in support of this conclusion. The visible color of the skin exerts no influence on its absorbing power in the infra-red. The absorption and emission of infra-red radiation occurs in the outer layers of the skin. The infra-red transmission spectrum of skin has a characteristic fine structure which may prove to be of physiological interest.

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SUMMARY

1. The emission spectrum of human skin has been studied and found to be essentially that of a black-body radiator.
2. The infra-red transmission and reflection spectra are such as would be expected of a black-body radiator.
3. The infra-red transmission spectrum of skin epidermis has been found to have a characteristic structure. The most prominent absorption bands are situated in regions where there are known to be strong bands due to C-H, N-H, and O-H linkages.

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